Green nephrology

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Abstract | Clear evidence indicates that the health of the natural world is declining globally at rates that are unprecedented in human history. This decline represents a major threat to the health and wellbeing of human populations worldwide. Environmental change, particularly climate change, is already having and will increasingly have an impact on the incidence and distribution of kidney diseases. Increases in extreme weather events owing to climate change are likely to have a destabilizing effect on the provision of care to patients with kidney disease. Ironically, health care is part of the problem, contributing substantially to resource depletion and greenhouse gas emissions. Among medical therapies, the environmental impact of dialysis seems to be particularly high, suggesting that the nephrology community has an important role to play in exploring environmentally responsible health-care practices. There is a need for increased monitoring of resource usage and waste generation by kidney care facilities. Opportunities to reduce the environmental impact of haemodialysis include capturing and reusing reverse osmosis reject water, utilizing renewable energy, improving waste management and potentially reducing dialysate flow rates. In peritoneal dialysis, consideration should be given to improving packaging materials and point-of-care dialysate generation.

During the past century, human populations have experienced unparalleled health gains. Global average life expectancy has almost doubled, whereas child and maternal mortality have decreased by around 9-fold and 100-fold, respectively[1–3]. Despite the ageing of the world's population, the global total disease burden, measured in disability-adjusted life years, has steadily declined, as has the number of people living in extreme poverty[4,5]. In addition, human populations have collectively (although not equally) benefited from better health care, improved education, major technological advances and increased wealth.

Such progress has, however, come at considerable environmental cost. Less than a quarter of all land on Earth remains free from the direct impact of human activities, with this figure predicted to fall to 10% by 2050 (REFS[6,7]). Over one-third of all the land surface has been converted into farmland, and annually, nearly 75% of freshwater resources are appropriated for agricultural use[6,8]. Human activities have led to the extinction of 60% of mammals, birds, fish and reptiles since 1970, with a further 1 million animal and plant species threatened with extinction, many within decades[8]. Each year, 4.8–12.7 million metric tonnes of plastic[9] and 300–400 million tons of heavy metals, solvents, toxic sludge and other wastes from industrial facilities[8] are allowed to enter the oceans. In addition, anthropogenic greenhouse gas emissions have increased 2-fold since 1980, raising the average surface temperature of the Earth by about 1.0 °C above pre-industrial levels[8]. This global warming is presenting unprecedented risks, not only to natural systems but also to human health[10,11].

It is becoming increasingly clear that as a species, we are well and truly living beyond our means. As noted in the 2005 Millennium Ecosystem Assessment report, "human activity is putting such strain on the natural functions of Earth that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted"[12]. If we are to maintain the health gains achieved over the last century, urgent action is required to conserve natural resources and reduce the impact of people on the planet. New ways of thinking and doing are required from all levels of society and across all sectors, including health care.

Importantly, health-care systems, particularly in the developed world, consume vast resources and make a substantial contribution to greenhouse gas emissions. In 2013, over 10% of total US emissions arose from the health-care sector[13], whereas 7% of total Australian emissions arose from the health-care sector in 2014–2015 (REF.[14]). In the UK, where substantial efforts have been made to address the carbon footprint of health care, the contribution of this sector to total emissions in 2015 was lower at 4%[15].

Haemodialysis programmes have a particularly large carbon footprint, with a recurrent, per capita resource consumption and waste generation profile that seems to be disproportionately high compared with most other medical therapies[16–18]. Although fewer data are available on the carbon footprint of peritoneal dialysis (PD), the

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https://doi.org/10.1038/s41581-019-0245-1

Key points

- A bidirectional relationship exists between the environment and kidney diseases; environmental change will increasingly have an impact on patterns of kidney diseases, whereas kidney care is responsible for substantial carbon emissions and resource depletion.
- Haemodialysis consumes vast quantities of water and energy and produces high volumes of waste, whereas peritoneal dialysis requires the use of peritoneal dialysis fluids that are packaged in plastic and transported across and between countries to the point of care.
- Multiple strategies exist to improve the environmental profile of haemodialysis, including recycling reverse osmosis reject water, reducing dialysate flow rates, utilizing renewable energy sources and optimizing waste management; many of these strategies also apply to peritoneal dialysis.
- An additional opportunity to reduce the environmental impact of peritoneal dialysis arises from point-of-care dialysate generation.
- A limited number of dialysis facilities and professional organizations worldwide have taken preliminary steps to improve the environmental profile of dialysis; however, much work remains to be done.
- A need exists for improved monitoring of dialysis resource usage and waste generation, widespread uptake of environmental improvement opportunities by dialysis facilities, increased environmentally themed research and a greater focus on preventative care.

high usage of consumables and resultant waste generation together with the high frequency of treatments suggest that the environmental impact is likely to be substantial.

In this Review, we outline the relationship between environmental change and kidney diseases and discuss the environmental impact of kidney care delivery, with a focus on dialysis. We also highlight the existing opportunities to reduce the carbon footprint of kidney care as well as areas for future research.

Environmental change and kidney disease

Over the past decade, understanding of the relationship between environmental change, particularly climate change, and human health has increased rapidly[10,11]. The effects of climate change on health are broad and mediated through increases in extreme weather events; altered distributions of vector-borne and other climate-sensitive diseases; reductions in crop yields, fish stocks and fresh water availability; and social unrest and population displacement (FIG. 1). Together, these factors are now viewed as the greatest public health challenge of the twenty-first century[10,11,19].

Many of these factors can also have an impact on the patterns and distribution of kidney diseases[20,21] (FIG. 2). Extreme heat days, which are predicted to become more frequent and severe over the coming decades, increase the insensible loss of body water and salt. This loss can lead to fluid deficit, vasoconstriction, reduced kidney perfusion and associated acute kidney injury (AKI). Multiple studies have reported increases in hospital admissions for AKI during heat waves[22–27]. During the severe European heat wave of 2003, kidney failure was a documented cause of excess mortality[28]. Higher temperatures also promote nephrolithiasis; the primary mechanism is thought to be volume depletion, which leads to a compensatory reduction in urine volume with subsequent urinary supersaturation with stone-forming salts[29]. Models suggest that if the current rate of temperature rise is sustained, the number of lifetime cases of stone disease in the USA will increase by 2 million by 2050 (REF.[30]). The estimated cost of this increase to the US health-care system is US$0.9–1.3 billion annually.

Extreme heat combined with strenuous work and water shortage has also been associated with epidemics of early onset chronic kidney disease (CKD) in diverse regions of the world including Central America, Sri Lanka, India, the Middle East, Africa, North America and South America[31–33]. Although the underlying cause of CKD in these cases remains controversial, there is general agreement that heat stress is likely to be a key contributor, possibly exacerbating damage caused by an environmental toxin found in pesticides, soil or drinking water[34]. The kidney is particularly vulnerable to environmental toxins because once systemically absorbed, many of these toxins are concentrated in the kidney during filtration. Although the available data are currently limited, evidence of an association between environmental pollutants and a range of kidney diseases is increasing[35].

The frequency and intensity of floods are also predicted to increase because of climate change, as is the geographic distribution of disease vectors such as mosquitoes[10,36]. These changes will increase the risk of diarrhoeal illnesses and infections such as leptospirosis, hantavirus, malaria and dengue, which are major causes of AKI in low-income and tropical regions[37]. Other environmental changes such as deforestation and urbanization will create additive risk, with loss of habitat and food sources driving animal and insect species into greater contact with humans[12].

Climate change is also likely to have a destabilizing effect on the provision of health care to patients with kidney diseases. Extreme weather events can interrupt critical infrastructure including power, water, transportation and telecommunication services. Such disruption can have a negative impact on access to haemodialysis facilities, transport of haemodialysis and PD supplies and the availability of critical medical care and medications, including immunosuppressants for kidney transplant recipients.

The environmental impact of dialysis

In 2018, 3,362,000 people were estimated to be receiving dialysis worldwide, with 2,993,000 (89%) receiving haemodialysis and 369,000 (11%) receiving PD[38]. Importantly, the global dialysis population continues to grow every year and is projected to reach close to 5 million by 2025 (REF.[39]). When these numbers are considered in the context of the resources used and waste generated per dialysis treatment, the enormity of the environmental impact of this single medical intervention becomes apparent[40].

Haemodialysis

Water usage. Large-volume, high-quality water is central to the provision of haemodialysis. Prior to being used for haemodialysis, source water must be extensively treated to remove contaminants and inorganic ions and reduce hardness[41]. A core step in this process is reverse osmosis (RO) water filtration, which involves

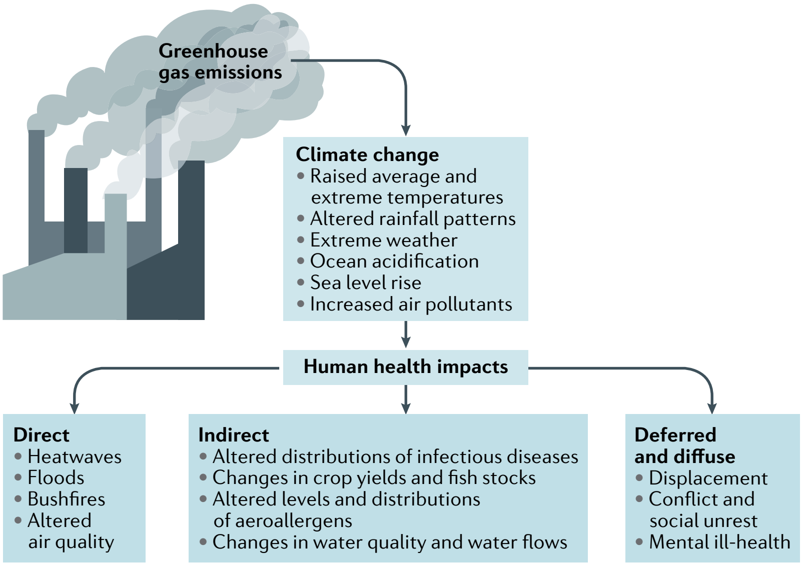

Fig. 1 | **Greenhouse gas emissions, climate change and human health.** Climate change owing to high levels of greenhouse gas emissions poses a broad range of threats to human health and survival[11]. The impacts of climate change on human health can be direct (for example, heatwaves cause heat stress and other heat-related illnesses), indirect (for example, warmer temperatures lead to an increased range of mosquitoes and alterations in the incidence and distribution of mosquito-borne diseases), or deferred and diffuse (for example, water shortages can lead to conflict and forced migration with associated ill-health).

using hydrostatic pressure to force water across a semipermeable membrane that removes any remaining dissolved ions and salts (FIG. 3). Many of the RO systems currently in use are inefficient, rejecting between half and two-thirds of the source water at the RO membrane. This inefficiency means that for a dialysate flow rate of 500 ml/min, 1 l or more of source water per minute is required to prepare the dialysate, or 240 l over a 4-h dialysis session. As pretreatment priming, rinsing and sterilization of the system also requires water, total water draw per patient, per haemodialysis treatment, can reach 500 l.

Historically, any unused permeate and all water rejected at the RO membrane was sent to the drain. However, improvements in modern haemodialysis systems can reduce water wastage. Many systems are now able to automatically adjust the flow of water to match actual usage[42]. Flow rate is reduced when few patients are dialysing and machines are in standby mode or undergoing disinfection, leading to lower production of pure water for dialysate preparation and lower water wastage by the RO unit. In addition, some systems now have the ability to recirculate unused permeate and a proportion of the RO ‘reject’ water back to the inlet to be passed through the RO membrane again. The most efficient of the available systems are able to recirculate or ‘save’ 80% of the water that would otherwise go to the drain[43].

Unfortunately, as a general rule, wasting water by setting a low recovery ratio (percentage of source water that is converted into pure water) is beneficial for the function of the RO unit and will extend the life expectancy of the RO membrane. Increasing the recovery ratio will increase the likelihood of organic fouling of the membrane or scaling by water hardness if a softener is not used. A recovery ratio >50% should therefore generally only be used for softened, non-fouling feed water, or where the cost of membrane replacement is low. Moreover, the most efficient RO systems are expensive, which precludes many haemodialysis facilities from purchasing them. The result is that many dialysis facilities still send ≥50% of source water to the drain.

Importantly, even if water wastage could be reduced to zero, the reliance of effective haemodialysis on a high dialysate flow rate means that this intervention will always remain water-hungry. The use of a dialysate flow rate of 500 ml/min mandates the delivery of 120 l of water to each patient over each 4-h treatment session or, for a patient dialysing three times a week, 18,720 l annually.

Power usage. Haemodialysis systems are also very power-hungry. A study from Australia reported the average power draw of a Fresenius 4008B haemodialysis machine in combination with an individual Gambro WRO 10-1 RO unit to be 6.2 kWh per session[44]. This value included the power required for equipment start up and priming, a 4.5-h haemodialysis treatment session and the rinse and disinfect cycle.

An audit of electricity usage performed within two satellite haemodialysis facilities attached to the Royal Melbourne Hospital Kidney Care Service, Melbourne, Australia (15 and 12 chairs, respectively), found that the average ‘operational day’ electricity consumption was 271.5 kWh and 325.0 kWh at the two sites (K.A.B., unpublished work). The central RO unit in each facility (both Gambro CWP 103) used between 61% and 75% of the total electricity consumed, while the dialysis machines (Gambro AK 95 and Gambro 200) used 9–13%. The electricity usage per dialysis treatment averaged 12.0 kWh and 19.6 kWh at the two facilities, respectively. By comparison, the average Australian household used 18.7 kWh per day in 2014 (REF.[45]).

Waste generation. Three main waste disposal streams exist in health care: hazardous (infectious) waste, general waste and waste for recycling. To mitigate the risk of infection, hazardous waste must be either incinerated or chemically sterilized prior to disposal in landfill at high environmental and financial cost. General waste goes directly to landfill, but toxins from this waste such as phthalates (found in many medical plastics) can leach into the soil and groundwater and become environmental and health hazards for many years[46]. In addition, organic waste in landfill emits methane, a greenhouse gas that is 21 times more potent in terms of global warming than carbon dioxide (CO_2)[47]. Optimal recycling reduces resource use compared with manufacture of a product from virgin materials[48], but the capacity to recycle varies by country, as does the cost.

Detailed information regarding the types and amounts of waste generated by haemodialysis is sparse. A dialysis facility from the UK reported the generation of 2.5 kg of hazardous waste per haemodialysis treatment, of which 38% was plastic[49]. The waste was composed of numerous materials and plastic types, although polyvinyl chloride (PVC) was the most common

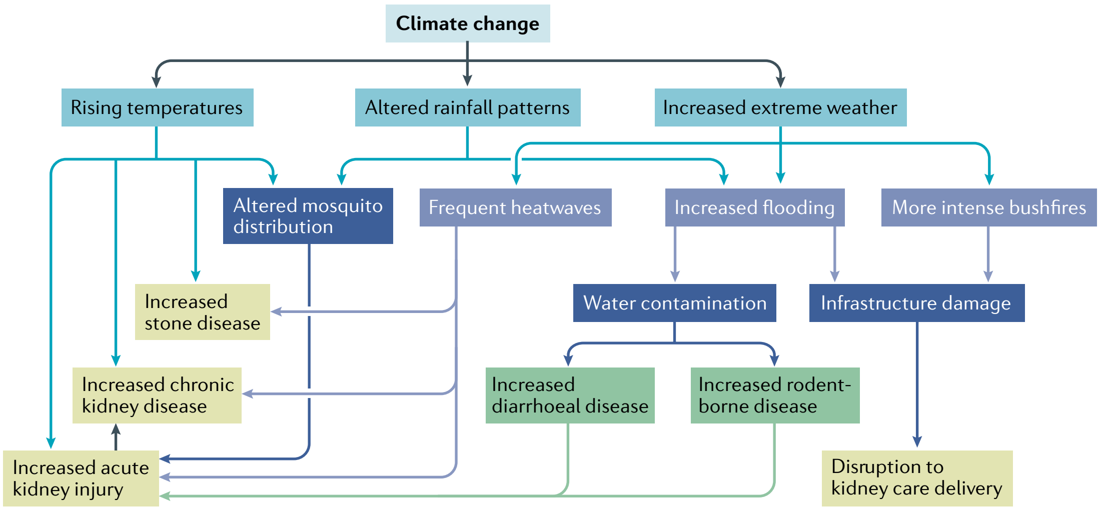

Fig. 2 | **The relationship between climate change and kidney diseases.** Climate change has the potential to have an impact on the incidence and distribution of acute and chronic kidney diseases through a variety of pathways. In addition, extreme weather events related to climate change are likely to have an increasingly disruptive influence on the delivery of health care to patients with kidney diseases.

(0.65 kg or 26% of the total). The outer packaging of individual items contributed another 0.075 kg, excluding cardboard, which was sent for recycling.

A study from Italy reported the generation of 1.5–8 kg of waste per treatment depending on the dialysis machine and choice of consumables[50]. Between 1.1 kg and 8 kg of this waste was disposed of as hazardous waste; the amount was determined by the degree to which waste was properly segregated by dialysis staff. Importantly, less than one-third of the non-hazardous waste was potentially recyclable.

Carbon footprint. Carbon footprint studies examine the total amount of CO_2 emissions that are directly and indirectly caused by an activity or accumulated over the life stages of a product[51]. When estimating the carbon footprint of haemodialysis, factors that would typically be considered include energy, water and consumable usage, waste generated by the haemodialysis procedure and the distances travelled and modes of transport utilized by patients and staff. These 'activity' data are converted into a common measurement unit of tonnes of CO_2 equivalents (t CO_2-eq) using standard emission factors[16].

A limited number of studies have looked at the overall carbon emission impact of haemodialysis. In a study of thrice-weekly in-centre haemodialysis in the UK, emissions of 3.8 t CO_2-eq were reported per patient, per annum[17]. This value is more than seven times the mean per patient carbon footprint in UK health care[18]. Home haemodialysis was responsible for greater emissions: 7 h of haemodialysis six nights a week resulted in emissions of up to 7.2 t CO_2-eq per patient per annum, depending on the regimen. In Australia, the carbon footprint of conventional haemodialysis has been estimated to be 10.2 t CO_2-eq per patient per annum[16], which is more than two-thirds of the estimated Australian mean annual per capita CO_2 emission of 15.4 t CO_2-eq[52].

Interestingly, in the Australian study[16], the largest shares of carbon emissions arose from pharmaceuticals (37.5%) and medical equipment (23.5%), with building energy use, water and waste making substantially smaller contributions[16] (pharmaceutical usage was not considered in the UK study[17]). This finding is consistent with broader health-care system data from the UK, where 21% of total emissions have been attributed to pharmaceuticals and 11% to medical devices[53]. However, despite their apparent large collective carbon footprint, very few data are available on the life cycle impact of individual pharmaceutical compounds or devices[54]. To our knowledge, no publicly available information exists on the carbon footprint or other environmental impact of the individual pharmaceutical compounds that are prescribed or the dialysis machines that are used in kidney care facilities on a daily basis.

Peritoneal dialysis

Water usage. PD uses far less dialysate than haemodialysis, in the order of 6–12 l per patient per day depending on the dialysis prescription. However, as with haemodialysis, it can be assumed that several litres of source water are used to generate each final litre of the pure water that becomes the dialysate. Moreover, dialysate for PD comes packaged in plastic. Although the water footprint of plastic varies depending on the type and production method, creation of 1 kg of plastic is generally considered to require around 180 l of water[55]. An empty 2-l PD dialysate bag weighs 155 g, suggesting water usage during manufacture of around 28 l per bag. Notably, the precise amount of water used is not publicly known because of the proprietary nature of PD fluid production.

Waste generation. The data on waste arising from PD procedures are even more sparse than that available for haemodialysis. A report from the UK described the generation of 1.69 kg of solid waste per day from patients receiving continuous ambulatory PD performing four daytime exchanges[49]. Of this waste, 0.94 kg or 56% was

PVC. Although this amount was less than that generated per haemodialysis treatment at the same centre (2.5 kg), the annual waste generation per patient on PD was estimated to be higher than that per patient on haemodialysis because of the daily nature of PD therapy (617 kg versus 390 kg). No study has reported on waste generation from automated PD.

Carbon footprint. To our knowledge, only one study has examined the carbon footprint of PD. This study was conducted at a single centre in China and involved patients treated with either continuous or daily ambulatory PD with a daily dialysate dose of 8 l (REF. 56). The results showed that 80% of the carbon footprint of PD was attributable to packaging materials (plastic dialysate bags, outer packaging and cardboard boxes), with the remainder mainly due to electricity usage and waste disposal. The overall carbon footprint of PD totalled 1.4 t CO_2-eq per annum, a figure that is substantially lower than that reported for haemodialysis in the studies discussed above[16,17]. However, the carbon impact of pharmaceutical use and of transporting PD fluids from the point of manufacture to the point of care were not considered. Given that both are likely to be very important contributors to the carbon footprint, more definitive assessments are needed to determine whether PD is more environmentally friendly than haemodialysis.

Opportunities for improvement

Given the high resource and carbon impact of dialysis, moral imperatives exist for dialysis services to consider ways of reducing their environmental footprint, and regulatory imperatives are likely in the future. In addition, it will be essential for dialysis services worldwide to implement targeted actions to reduce costs if the current quality of care is to be maintained or improved in the face of ever-growing service demands. Fortunately, many of the changes that are needed to improve environmental sustainability in health care also have the potential to deliver financial sustainability. Furthermore, many examples of where and how changes can be made already exist.

Haemodialysis

RO reject water recycling. A common misconception is that RO reject water is in some way contaminated. In fact, this water is highly purified source (tap) water that has passed through carbon and sand filters to remove particulate matter, chlorine, chloramines and other waste products. The reject water never contacts the dialyser or the patient; thus, it poses no more infectious, or other, risk (indeed far less risk) than the source water.

To prove this point, in 2004, a kidney care service from Australia performed detailed analysis of its RO system reject water and showed that apart from a mild increase in conductivity, it was indistinguishable from local drinking water and fell well within the limits set by the World Health Organization for potable water[57,58]. This group then pioneered the concept of capturing and reusing the reject water for other purposes[58]. Very simply, this approach involved the redirection of reject water from the RO unit into a nearby storage tank rather than down the drain. The water was then pumped to a holding tank on the eighth floor of the hospital building and gravity-fed to other areas of need, including the hospital's central sterilizing department (for steam generation), toilets, janitor stations and gardens. The same principles were employed in the home setting, with a tank, the necessary piping and a pump incorporated on a routine basis into home haemodialysis installations. This approach allowed patients to use their reject water in their laundries, toilets, gardens and elsewhere and to some extent offset the increased water costs they incurred from dialysing at home.

Subsequently, a limited number of other dialysis services have reported capturing and reusing RO reject water[42]. Illustrating the potential benefits of incorporating water-saving infrastructure into a new-build dialysis unit, one UK service described a recouping of implementation costs within a few months of unit opening, with recurrent savings of up to 4,492,000 l of water and £10,558 per year thereafter[59]. UK, Australian and French data have also shown that retrofitting water-conserving equipment to existing RO systems can be financially viable and even profitable[60–62], although the costs are influenced by the ease of installing pipe-work and storage

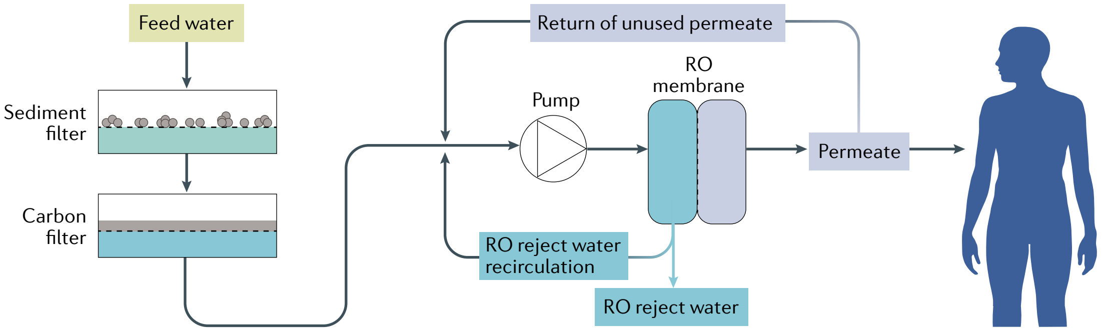

Fig. 3 | **Water treatment in haemodialysis.** Feed water is passed through a sediment filter to remove suspended solids and then a carbon filter to remove chlorine, chloramines and organic matter by absorption. The water is then pumped across a semi-permeable membrane that removes any remaining dissolved ions and salts via reverse osmosis (RO). This treatment produces water of a quality suitable for haemodialysis. The by-product is a similar volume of RO 'reject' water. Modern RO systems have the ability to recirculate a proportion of the reject water along with any unused permeate back to the inlet to be passed again through the RO membrane, thereby reducing water wastage.

tanks in existing buildings and opportunities for reject waster reuse[62].

Notably, despite the simplicity of the methodology and the potential for water and cost savings for dialysis services and home patients, we are not aware of legislation in any country that requires consideration of RO reject water capture and reuse in haemodialysis services. Such consideration should be a mandatory requirement for new-build dialysis units, as should consideration of other features of passive eco-building design.

Reduced dialysate flow rates. Since the 1960s, dialysate flow rates (Qd) have been routinely maintained at 500 ml/min, which was considered to be optimal for the dialysers in use at the time[63,64]. However, improvements in modern dialysers, including changes in fibre packing density and taper design, undulation of fibres and the addition of spacer yarns in the fibre bundle, enable better dialysate flow distribution across the dialysate compartment[65–70] and theoretically reduce the need for a high Qd to obtain adequate clearances.

Over the past decade, a limited number of studies have examined the impact of reduced Qd on dialysis adequacy. A single-centre crossover study found minimal benefit of increasing dialysate flow rates above 400 ml/min on urea clearance (Kt)[71]. Treatment with a Qd of 500 ml/min used 24 l more dialysate per 4-h session than treatment with a Qd of 400 ml/min, whereas further increasing Qd to 700 ml/min used an additional 48 l. A randomized crossover study in patients with body weights <65 kg reported that reducing Qd from 500 ml/min to 400 ml/min had no impact on Kt/V, interdialytic weight gain, blood pressure or electrolytes, but did decrease per-treatment dialysate consumption from 120 l to 96 l (REF.[72]). Another study compared Kt/V when dialysis was performed at Qd 500 ml/min, 700 ml/min and as determined by an AutoFlow function, which automatically adjusted Qd according to the effective blood flow of the individual patient and achieved a mean Qd of 404 ± 21 ml/min (REF.[73]). Although minimal benefit was seen by increasing Qd above the level dictated by the Autoflow function, the lower Qd seen with AutoFlow reduced dialysate and acid concentrate use by 20% and bicarbonate powder use by 23%. A study that used blood flow rates of 150–200 ml/min found that reducing Qd from 500 ml/min to 400 ml/min reduced urea, creatinine and phosphate clearance when the blood-to-dialysate flow rate ratio fell below 1:2 (REF.[74]). These data suggest that a threshold blood flow rate may be necessary to maintain dialysis efficiency in the context of a reduced Qd.

Importantly, follow-up in these studies was short (4–24 weeks) and none examined the longer term clinical outcomes of dialysing with reduced Qd. However, a Colombian study published in abstract form in 2019, reported similar dialysis adequacy, calcium, phosphate and parathyroid hormone concentrations in patients weighing <70 kg dialysing with a Qd of 400 ml/min versus 500 ml/min (REF.[75]). Moreover, adjusted mortality was similar between the groups over a minimum follow-up period of 2 years. Full publication of this study is needed, as are confirmatory studies in other populations. However, the available data suggest that a more considered approach to Qd is likely to be appropriate. Reducing dialysate usage by ~20 l per treatment might seem like a small improvement, but a similar volume of RO reject water will also be saved and the potential for water savings is large when the global haemodialysis population is considered.

Haemodialysis wastewater reuse. Haemodialysis wastewater (the spent dialysate containing uraemic waste that exits the dialyser) is uniformly discarded to the drain by all dialysis services worldwide. However, a single study from Morocco has investigated the potential of recycling this water for irrigation, landscaping and agricultural purposes[76]. In this study, RO reject and wastewater were together collected from the outflow pipe that drained from the haemodialysis unit into the municipal sewage. Testing of the water showed levels of organic matter and bacterial counts that fell within the limits set by the World Health Organization and the United Nations Food and Agriculture Organization for wastewater for agricultural purposes. The only difference between the haemodialysis wastewater and water that is considered to be suitable for agricultural use was an increase in conductivity, which the researchers suggested could be treated through processes such as RO or nanofiltration. The estimated costs of these treatments were high, but substantially lower than the costs of other water treatment processes currently in use, such as desalination.

Although there is currently no evidence that environmental contamination by wastewater from haemodialysis of patients with infectious diseases poses any practical risk, the theoretical risk, combined with the cost, make it unlikely that wastewater recycling by dialysis services will become widespread in the near future. However, with water scarcity predicted to impact two-thirds of the world's population by 2050 (REF.[77]), this concept might eventually be revisited.

Renewable power generation. There are currently limited options for reducing power consumption by haemodialysis systems. However, the impact of electricity usage on the carbon footprint of haemodialysis is dependent not only on the energy requirements of haemodialysis systems but also on the fuel sources or technologies used for local electricity generation. A study from Australia demonstrated that in the state of Victoria, which relies heavily on highly polluting brown coal, 18.6% of total dialysis emissions were attributable to electricity[16]. Conversely, in the state of Tasmania where electricity supply is mainly from hydro sources, the contribution of electricity to total emissions was substantially lower at 5.2%.

The global uptake of renewable energy sources is rapidly accelerating[78] and over time, this change will substantially reduce the carbon burden of electricity usage in haemodialysis. In the shorter term, individual dialysis facilities might consider localized solar system installations.

Only one study of solar augmentation of dialysis power exists in the literature. In 2012, Agar et al.[44] showed that a 3-kWh solar array on the roof of a four-chair home haemodialysis training unit in Australia reduced grid power consumption by 91% and power costs by 76.5%. Despite the high capital cost of the system (Australian $16,219), a return on investment was estimated at 7–8 years, with cost-free power generation for the life of the solar array thereafter. Importantly, rooftop solar costs have subsequently decreased in Australia and elsewhere[79]. The time to return on capital investment would therefore be substantially shorter today, in the order of 3–4 years in Australia for a similar sized system.

Efficient water purification. Achieving more substantial reductions in water and power usage in haemodialysis will require a move away from RO as a means of purifying water towards more efficient technologies. Vapour compression distillation may be one such technology. The Slingshot water purification unit is a relatively compact and lightweight device (<140 kg) that uses vapour compression distillation to convert water from any source into potable water[80]. This device can produce up to 850 l of water per day with little wastage and uses less than 1 kW of electricity per hour.

Use of the Slingshot for provision of safe drinking water has been piloted in schools, health clinics and community centres in developing regions where access to potable water is limited[80]. To our knowledge, it has not yet been trialled as a means of treating water for haemodialysis. Whether or not this device is capable of producing the quality and quantity of water that is required for haemodialysis at a reasonable cost remains to be demonstrated, but given its potential to reduce haemodialysis resource use, study of this application seems to be warranted.

Sorbent haemodialysis. In the future, sorbent technology may also provide a means of dramatically reducing both water and power usage in haemodialysis. In short, sorbent dialysis involves recirculating and reconstituting spent (effluent) dialysate rather than sending it to the drain (FIG. 4), as occurs during conventional haemodialysis[81,82]. Sorbent technology not only removes the need for a continuous water source but also vastly reduces the overall volume of water required for the haemodialysis treatment (typically ~6 l are used)[81,82]. Other advantages of sorbent dialysis systems include reduced power usage, smaller size, increased portability and an ability to obtain water of a higher purity than can be achieved by conventional haemodialysis systems.

Interestingly, sorbent dialysis is not a new technology. Between 1960 and 1980, a sorbent system known as REDY (recirculation of dialysate) was widely used in clinical practice alongside conventional haemodialysis systems[81]. However, use of this system ceased completely by the early 1990s, largely for reasons of cost. Over the early part of this century, a number of new and improved sorbent-based systems were evaluated in clinical trials and some of these were approved for use by the US Food and Drug Administration[81,82]. However, these systems were never marketed for mainstream use, for unclear reasons.

In the past 15 years, there has been a resurgence of interest in sorbent technology in the form of the Wearable Artificial Kidney (WAK), a miniaturized, sorbent-based, battery-operated haemodialysis system designed for continuous use[83]. A small clinical trial reported adequate clearances and high patient satisfaction with 24 h of WAK application[84]. However, a large range of technical issues were encountered (e.g. excessive carbon dioxide bubbles in the dialysate circuit, clotting of the blood circuit and fluctuating blood and dialysate flows), suggesting that it will be some time, if ever, before the WAK becomes commercially available and helps to solve the issues of water and power usage in haemodialysis.

Waste segregation, recycling and minimization. Effective waste segregation is a key first step in reducing the environmental and financial burden of haemodialysis waste

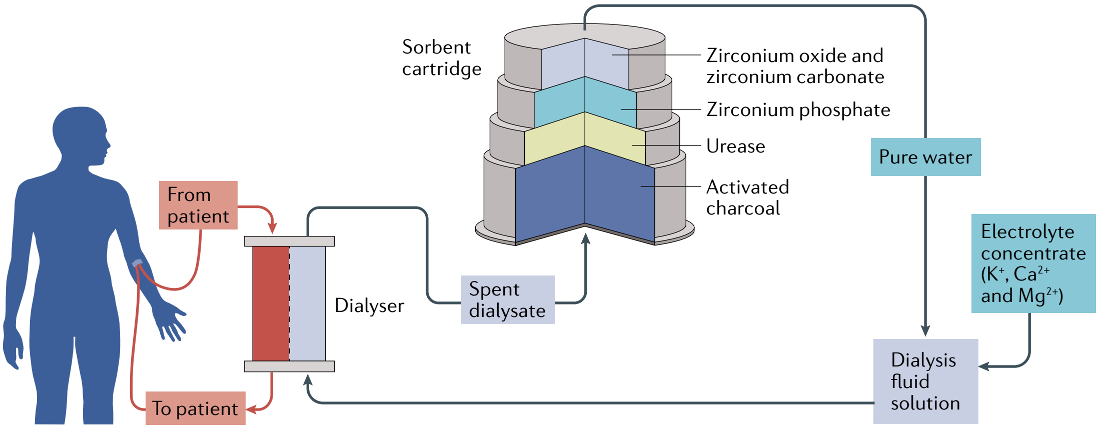

Fig. 4 | **Schematic of a sorbent dialysis system.** Sorbent dialysis systems recirculate and reconstitute spent (effluent) dialysate rather than sending it to the drain. The spent dialysate exits the dialyser then passes through a multilayered sorbent cartridge. The first layer contains activated charcoal, which adsorbs heavy metals, chloramines, creatinine, a range of middle-molecular-weight molecules and other organic matter. The second layer contains urease, which converts urea into carbon dioxide and ammonia. The third layer contains zirconium phosphate, which releases sodium and hydrogen while binding ammonium, calcium, magnesium, potassium, other cations and metals. The final layer contains zirconium oxide and zirconium carbonate, which release sodium, bicarbonate and acetate in exchange for phosphate, fluoride and metals. The pure water that emerges from the cartridge is mixed with an electrolyte concentrate before being returned to the dialyser.

Table 1 | **Cumulative savings from UK Green Innovations**[98]

Type of innovation	Initiatives undertaken by individual kidney care facilities	Environmental and financial savings	Potential financial savings to the UK health system
Infrastructure projects	Reverse osmosis reject water reuse; installation of baling machines for plastic and cardboard recycling; lighting upgrades; central delivery of acid for haemodialysis; retrofitting of heat exchangers to dialysis machines; upgrade to water treatment plant	The six projects had capital investment costs of £121,000, but generated annual savings of £57,000, 84 tonnes of greenhouse gases and 12 million litres of water	Estimated savings of £7 million (US$10.64 million), 11,000 tonnes of greenhouse gases and ~470 million litres of water if infrastructure innovations were replicated by 30% and process innovations by 60% of UK kidney care units; model-of-care estimates were not included in the total savings projections
Process innovations	Paperless laboratory reporting; waste reductions in food, linen and dialysis consumables; improved waste segregation	No investment costs were incurred; annual savings of £186,000 and 183 tonnes of greenhouse gases	
Model of care innovations	Improved use of telecommunications	Financial savings were not quantified owing to the complexity, but savings of 6 tonnes of greenhouse gases were estimated from three specific projects in their pilot phase	

disposal. A study from Italy demonstrated that by simply emptying residual fluids from receptacles and directing all haemodialysis waste to the appropriate stream, up to 7 kg less hazardous waste could be generated per haemodialysis treatment[50]. Best, as opposed to worst, practice waste management had the potential to save on average €10 (US$13) per treatment for very little additional staff time (~1 min for haemodialysis and 2 min for haemodiafiltration). The researchers estimated that optimal management of waste across dialysis facilities worldwide could save €3 billion (US$4 billion) annually.

Optimization of recycling is also beneficial. For example, PVC is typically disposed of as general or hazardous waste. This approach creates the potential for leaching of plasticizers into the soil and groundwater from landfill or the release of toxic dioxins if the PVC is incinerated[49,85,86]. However, PVC can be recycled at no or very low cost into hosing or floor mats for children and workplaces[87]. Each tonne of recycled PVC replaces a similar weight of virgin PVC compound, thereby off-setting the carbon footprint of new products[87].

Dialyser reuse might be considered to offer another opportunity to reduce solid waste in haemodialysis. However, this practice would lead to an increase in liquid waste from the germicides used for dialyser disinfection. Study of the environmental impact of single-use versus the reuse of dialysers would be required before the latter could be recommended on environmental grounds, the fact that questions remain regarding the safety of reuse and whether it leads to costs savings notwithstanding[88].

Beyond segregation and recycling, machines now exist that can steam, microwave or chemically sterilize then shred hazardous waste at the point of care. The end product can be disposed of as general waste at reduced cost or, more importantly, can be recycled. In Australia, an ongoing trial is examining the utility of adding shredded, sterilized waste plastic from haemodialysis procedures into concrete. Preliminary results suggest that adding this plastic may reduce water penetration and therefore corrosion of the concrete, improving the long-term quality and durability of the final product[89,90].

The implications of such projects are potentially far-reaching, not only for waste management in dialysis but also in the broader health-care sector. However, attempts to control or manage waste after it has been generated will, at best, only partially address environmental impacts. A need exists for the design and production of eco-friendly dialysis disposables. These should have minimal packaging, be made from non-toxic, sustainably produced or recycled materials and be able to be reused, recycled or to biodegrade at the end of life. Greater focus on the issue of waste by the medical community has the potential to drive industry to produce such products. Such efforts will be aided in some regions by broader government directives, for example, the EU has mandated that all plastic packaging in the EU market must be either reusable or easily recycled in a cost-effective manner by 2030 (REF.[91]). Incentives have also been provided for producers to take environmental considerations into account, from the design phase to the end of life of their products[91].

Carbon accounting for pharmaceuticals and devices. At the simplest level, clinicians can contribute to reducing pharmaceutical and device emissions by avoiding unnecessary interventions, use of diagnostic tests and prescription of medications. However, a need also exists for reliable information on the life cycle impact of individual drugs and devices. In 2012, the UK National Health Service (NHS) Sustainable Development Unit, together with pharmaceutical and medical device industries, developed an internationally applicable guideline to aid in consistent greenhouse gas accounting and reporting for pharmaceuticals and medical devices[53]. The aim of this document is to provide industry with a means of identifying emission 'hot-spots' and thereby focusing their efforts on reducing greenhouse gas emissions.

At the local level, the widespread inclusion of sustainability criteria into procurement contracts would provide incentive for industry groups to use this guidance. Such criteria would also be a powerful means of stimulating improvement activities among industry competitors.

Moving beyond carbon emissions, life cycle assessments are required to identify the broader environmental impacts of pharmaceuticals and devices (e.g. pollution and resource depletion). A need also exists to move from 'cradle to grave' evaluations, which consider the impact of products from creation to disposal, to a 'cradle to cradle' approach, which ensures that the waste from one product or system becomes the building block of another. This approach is particularly important for dialysis machines and other equipment, which should be designed to ensure that component parts can be recycled and reused, ideally perpetually, rather than discarded at the end of life.

Peritoneal dialysis

Many of the potential approaches for improvements in haemodialysis energy, waste, pharmaceutical and device management discussed above also apply to PD. A particular need exists for more eco-friendly packaging materials in PD given the high volume of plastic used to package dialysate.

An additional area of impact for PD relates to the transport of dialysate from the point of manufacture to the point of care. Although the environmental burden this transport imposes remains to be quantified, a potential solution — namely, point-of-care dialysate generation — has been identified[92]. The Ellen Medical Affordable Dialysis System is a PD-based system that includes a miniature distiller that, similar to the Slingshot, is capable of producing pure water from any source[93]. This water can then be combined with concentrate to produce dialysate, circumventing the carbon impact and cost of transporting thousands of litres of dialysate across and between countries to each patient annually. In addition, the distiller is highly efficient; thus, water wastage from the purification process is minimal; approximately 10% in hard-water areas and as low as 2–5% in soft-water areas. The system runs off solar power, is light and portable and can be manufactured and sold for less than Australian $1,000.

The Ellen Medical Affordable Dialysis System was originally designed to address the problem of the many millions of people worldwide who need but cannot afford dialysis. However, this system also has the potential to substantially lower the environmental footprint of PD if used as an alternative to currently available systems. The design prototype for the Ellen Medical Affordable Dialysis System is currently being finalized, with clinical trials anticipated by 2020 (J. Knight, Director, Ellen Medical, Sydney, Australia, personal communication). Importantly, the designer of the system has also developed detailed plans for how this technology could be used for affordable, less resource-intensive haemodialysis[94].

Box 1 | **Green initiatives that can be undertaken in dialysis facilities**

Low- or no-cost initiatives

- Identify ‘green champions’ or establish a ‘green team’ within the facility
- Include environmental sustainability as a standing agenda item for departmental meetings
- Incorporate ‘green’ education into departmental meetings
- Encourage staff to turn off lights when not in use
- Ensure that computers and photocopiers are auto-configured to enter hibernation, sleep or standby mode when not in use
- Encourage staff to log off and switch off computers when not in use
- Ensure that thermostats are set at appropriate temperatures
- Ensure that heating and cooling are turned off when the unit is not in use
- Ensure that general and hazardous waste and recycling bins are available and appropriately sited and signed
- Incorporate waste education in staff induction and ongoing education programmes
- Explore local recycling opportunities (for instance, polyvinyl chloride or single-use metal instruments recycling)
- Request that dialysis product suppliers retrieve pallets, cardboard boxes and other packaging on delivery
- Explore opportunities to introduce or raise the weighting of environmental criteria in procurement contracts
- Discourage, monitor and/or restrict printing and photocopying
- Set printers and photocopiers to double-sided printing
- Explore opportunities for electronic record keeping and communications
- Promote the health benefits of active transport to patients and staff
- Provide incentives to those engaging in active transport (e.g. ‘ride-to-work’ breakfasts)
- Investigate and encourage shared transport options
- Explore opportunities to expand the use of telehealth

Initiatives involving an initial capital outlay

- Explore opportunities for renewable energy generation
- Explore the feasibility of recovering and reusing reverse osmosis reject water
- Investigate the installation of water-saving taps and toilets
- Upgrade lighting to low-energy light bulbs
- Install motion sensors to control lighting in low-traffic areas

Transplantation

To our knowledge, no published data are available on the environmental impact of kidney transplantation. However, it is reasonable to assume that this impact largely arises from the resource usage that is associated with the initial surgical procedure and the long-term administration of immunosuppressant medications. In economic studies, kidney transplantation is initially more financially costly than dialysis, but this situation reverses within years[95,96]. The same pattern would be expected for the environmental costs of transplantation. Increasing rates of kidney transplantation might therefore be a potential strategy to reduce the environmental impact of end-stage kidney disease care, but future studies are needed to confirm this hypothesis.

Green nephrology initiatives

As discussed above, a limited number of individual dialysis services have taken important steps towards monitoring and improving the environmental profile of dialysis delivery. More broadly, in 2009, a Green Nephrology network was established in the UK within the NHS Sustainable Healthcare Programme[97]. Involving clinicians, renal technicians, industry partners and patients, this initiative was responsible for a marked practice and culture change across the whole UK dialysis spectrum over an impressively short 3–4-year time frame. The Green Nephrology group has estimated potential annual savings to the UK health-care system of £7 million (US$10.64 million), 11,000 t CO_2-eq of greenhouse gases and ~470 million litres of water from ‘green’ innovations[98] (TABLE 1) . The success of this programme makes it an exemplar for others to follow.

In 2018, the European Renal Association-European Dialysis and Transplant Association committed to a broad range of initiatives aimed at ‘greening’ the kidney care sector[99]. The Australian and New Zealand Society of Nephrology has developed a position statement on green

Box 2 | Priorities for future green nephrology research

- Evaluate the impact of reduced dialysate flow rates on longer-term clinical outcomes
- Explore the potential for solar energy systems to offset the energy usage and costs of dialysis
- Develop and test new water treatment technologies for haemodialysis
- Evaluate the weight and types of waste generated from different haemodialysis machines and consumables sets
- Evaluate the weight and types of waste generated from different peritoneal dialysis systems and consumables sets
- Investigate new packaging materials and design (for example, bio-based or compostable plastics or plastics with superior recyclability)
- Investigate opportunities for on-use of sterilized mixed dialysis waste plastic
- Compare the carbon footprint of home- versus facility-based haemodialysis
- Evaluate the carbon footprint of peritoneal dialysis with the different peritoneal dialysis modalities and treatment regimens
- Evaluate the carbon footprint of transplantation, with a particular focus on the life cycle impact of immunosuppressant medications
- Investigate the utility of telemedicine for patient consultations

nephrology, funded environmental research prizes and upgraded an existing 'Green Dialysis' website (https://www.greendialysis.org) to provide practical information for those wishing to implement changes in their own facilities. In Brazil, a 'call to action' has been made by the national kidney society to the nephrology community[100].

Future strategies

In May 2019, the UN released a Global Assessment Report touted as the most comprehensive study of life on Earth ever undertaken[101]. This report issued a stark warning: "The health of the ecosystems on which we and other species depend is deteriorating more rapidly than ever. We are eroding the very foundations of economies, livelihoods, food security, health and quality of life worldwide"[101]. It made clear that although remediation is possible, this will require urgent, transformative change at every level from local to global[8,101]. In this context, we can no longer leave it up the next person, company, nation or generation to address the current ecological crisis; we must all act now. Within health care, the specialities with the greatest environmental impact should lead efforts to reduce the environmental impact. As dialysis seems to have one of the largest footprints of all, the nephrology community has a duty of care to develop comprehensive and innovative environmental programmes.

At the level of dialysis facilities, baseline auditing of water and energy usage and waste production should be a first priority. These data would assist in prioritizing subsequent environmental initiatives and provide a baseline against which to monitor progress. Moreover, many simple, low-cost 'green' measures can be implemented immediately (BOX 1). The next step is to consider larger environmental projects such as RO water recycling or renewable energy generation, which have the potential to provide both environmental and financial benefits. A need also exists for broader surveying of environmental attitudes, knowledge and practice patterns across world regions, as has previously occurred in the UK and Australia[102,103]. Environmentally themed research should also be promoted and supported (BOX 2).

Efforts must also move beyond reducing resource use and waste minimization. Although important, these actions alone will be insufficient to address the most carbon-intensive areas of health care. A need exists to identify and avoid unnecessary or wasteful interventions and develop and adopt more innovative models of care such as telehealth. This work could be undertaken by individual kidney care services and/or by national and regional societies.

Finally, an urgent need exists to advance preventive and primary care programmes. The prevalence of kidney diseases is increasing exponentially owing to population ageing and rising rates of diabetes, hypertension and obesity[104,105]. The most rapid increases are occurring in some of the poorest parts of the world, where limited or no treatment options exist. To mitigate the potentially devastating human, economic and environmental costs, addressing risk factors for kidney disease must be a priority.

Importantly, many climate change mitigation strategies have the potential to lead to improved health outcomes[11]. Climate change should therefore be considered not only a threat to health, but also an opportunity for health improvement. For example, investment aimed at shifting society away from car travel and towards active transport (e.g. walking or cycling) would not only reduce the substantial carbon emissions arising from the transport industry, but also the levels of air pollution and physical inactivity, which are both important risk factors for a broad range of chronic diseases including kidney diseases[106–109]. Similarly, initiatives that promote the adoption of more sustainable eating practices (namely, reduced consumption of animal products and increased consumption of vegetables, fruits, legumes, whole grains and nuts) would reduce the 30% of global emissions that is associated with agriculture, while at the same time reducing saturated fat intake and thereby the risks of obesity, diabetes, heart disease, nephrolithiasis and some cancers[110–112]. Moreover, evidence suggests that a balanced reduction in protein intake might slow CKD progression in patients with pre-existing kidney disease[113]. By promoting and supporting these no-regret options, the nephrology community could simultaneously accelerate progress to tackle climate change and drive improvements in kidney health.

Conclusions

Although environmental issues may seem like a distant concern from within busy dialysis facilities, the health and wellbeing of ourselves and our patients is fundamentally dependent on the health of the planet. Protection of the environment can no longer be seen as an optional extra once the more pressing concern of patient care has been dealt with. We hope that this Review will lead individuals, dialysis facilities and professional organizations to consider the steps they might take to enact change. By so doing, they will be contributing not only to the long-term sustainability of health-care systems but also to environmental health and therefore the health and wellbeing of current and future generations.

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Author contributions

K.B. researched the data for the article and wrote the manuscript. J.A. reviewed and/or edited the manuscript before submission.

Competing Interests

K.B. has received research grants from Fresenius Medical Care and Baxter Healthcare. J.A. has received research grants from Fresenius Medical Care and sits on the Medical Advisory Board for Quanta Dialysis Technologies.

Peer review information

Nature Reviews Nephrology thanks Melissa Bilec, Peter Blankestijn, Giorgina Piccoli and John Stoves for their contribution to the peer review of this work.

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